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RESEARCH SUMMARY

Sorption studies of ponderosa pine (Pinus ponderosa Laws.) needles and litter beds of current year cast show a shorter response time and lower equilibrium moisture contents than most other conifer needle data in the literature. For conditions below fiber saturation, the response time is described best by considering the time for 95 percent of the total change in moisture content. Equilibrium moisture content can be estimated by an equation based on temperature and humidity, but type of vegetation must be considered.

Analysis of moisture response at the test conditions indicates that the moisture diffusivity of the needles and beds remains nearly constant for both adsorption and desorption.

INTRODUCTION

The ponderosa pine (*Pinus ponderosa* Laws.) timber type covers nearly 9 million acres in the Rocky Mountains. The needle litter cast by these trees produces a highly flammable fuel when conditions are dry. The capability for fires to start and spread depends largely on the moisture content of surface fuels and their response to environmental changes. This report summarizes the results of laboratory tests to determine equilibrium moisture contents and adsorption-desorption timelags below fiber saturation of ponderosa pine needles. Conducting the tests at conditions below fiber saturation eliminated consideration of the movement of free water and possible leaching of the needles.

Research on fuel moisture over the past several years has added useful knowledge on fine forest fuels (Pěch 1968; Simard 1968a; 1968b; Nelson 1969; Van Wagner 1969 and 1972; Mutch and Gastineau 1970; Blackmarr 1971; and Fosberg 1975). Equilibrium moisture contents and timelags are the important moisture response characteristics of fine forest fuels (Byram;[1] King and Linton 1963) and are required in fire-danger rating and fuels appraisal systems. These two characteristics establish the moisture content at any time, depending on the environmental conditions. Equilibrium moisture content (EMC) is defined as the moisture content finally attained uniformly throughout a material exposed to an atmosphere of fixed temperature and humidity. This occurs when the vapor pressure in the fuel equals the vapor pressure in the atmosphere. Moisture response time, assumed to be an exponential response, is defined as the time required for a fuel to achieve 63.2 percent of the total change between its initial moisture content and EMC. This can be expressed as $1 - 1/e$ of the difference between initial moisture content and EMC, where e is the base of natural logarithms.

The test results presented here establish the EMC values at 75° F (24° C), and the sorption response times of needles and of fuel beds at three bulk densities, and report the effects of solar heating upon desorption. The tests with three fuel bed bulk densities were conducted at 80° F (27° C), with 90 and 20 percent relative humidity end points to determine if the response times were different from response times of individual pine needles. The bulk densities (the load per unit area divided by the depth of the layer) matched findings for litter beds of ponderosa pine needles in western Montana (Brown 1970).

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[1] Byram, George M. 1963. An analysis of the drying process in forest fuel materials. Paper presented at the 1963 International Symposium on Humidity and Moisture, Washington, D.C., May 20-23, 1963. 38 p. (Unpublished report on file at the Southern Forest Fire Laboratory, Macon, Georgia 31208).

METHODS

Equipment

The EMC's of ponderosa pine needles were obtained over a range of relative humidities (16 to 88 percent) at ambient air temperature of 75° F ±5° (24° C ±2°) by means of two preconditioning cabinets and a final conditioning cabinet. One preconditioning cabinet provided a high humidity (95 percent) environment at ambient air temperature with open trays of water. The other preconditioning cabinet provided a hot-dry environment of 2 to 6 percent relative humidity by simply heating the ambient air to 120° F (49° C). The final conditioning cabinet was maintained at a fixed relative humidity by use of saturated-salt solutions at the 75° F ±5° ambient temperature. Temperatures within the cabinets were measured with mercury thermometers accurate to ±1° F and relative humidity was determined by standard psychrometer procedures and by dewpoint measuring equipment accurate to ±1° F.

The salt solutions used and the measured relative humidities for each were:

Salt	$LiCl$	$MgCl_2$	$Mg(NO_3)_2$	$NaCl$	KNO_3
Percent relative humidity:	13	33	53	71	91

The moisture content of the needles was determined by withdrawing samples for xylene reflux distillation (Buck and Hughes 1939). Initial frequent sampling showed the moisture content to be within 1 percent moisture content of EMC after 1 week in most cases. Two samples were taken at each measurement period.

The response time tests were conducted at 80° F (27° C), with step changes in humidity from 90 to 20 percent and return. A conditioning cabinet was used to prepare the needle moisture content prior to the response test. Then, a programable environmental chamber provided a shift in relative humidity so a moisture response could be induced. The moisture response was measured as a weight change with unbonded, temperature-compensated strain gage transducers, load cells, and microscales. Sensitivity of the weighing systems was adjustable so weight changes to 0.01 g could be resolved. Values of air temperature, relative humidity, dewpoint, solar heat, and weight loss were recorded on charts for each moisture response test. The conditions in the environmental chamber were controlled to ±2° F air temperature; ±2 percent at 20 percent relative humidity, and ±4 percent at 90 percent relative humidity; and ±0.01 of a solar constant.

Airspeed within the test volume of the environmental chamber was found to average less than 0.50 mi/h and be rather turbulent. Variability above the center of a litter bed was found to be from near 0 to 0.60 mi/h. This may have affected the response time of the fuel beds by providing more turbulent airflow than occurs in natural sites. Air velocity within a needle litter bed with a bulk density of 0.94 lb/ft^3 (0.015 g/cc) averaged less than 0.160 ft/s (4.88 cm/s), or 0.11 mi/h.

Needles and Litter Beds

The needles used in all tests were first-year cast, collected in September and October. The needles were sorted to remove broken needles and those separated from the fascicle. This tended to eliminate differences in moisture responses because of physical defects. The general physical properties of these ponderosa pine needles are (Brown 1970):

Particle density	31.8 lb/ft^3 (0.51 g/cc ±0.046)
Surface area/volume	1,755 ft^2/ft^3 (57.57 cm^2/cm^3 ±6.81)
Average thickness	0.027 in (0.0695 cm)
Shape factor	1.3

The litter beds of the needles for the EMC tests were placed in two wire screen containers to occupy a bulk density of 0.94 lb/ft^3 (0.015 g/cc). This bulk density is the medium value found by Brown (1970); the values for the light, medium, and heavy bulk densities were, respectively, 0.31, 0.94, 2.81 lb/ft^3 (0.005, 0.015, and 0.045 g/cc) and were used for the tests of bulk density effects on moisture response times. The needles were loaded to a depth of 2 cm for each bulk density. Litter beds for the EMC tests were preconditioned at a high and at a low relative humidity until stabilized with their environment, then transferred to a final conditioning cabinet at a controlled humidity and allowed to stabilize. Stabilized conditions were considered to be achieved when consecutive moisture content determinations were within ±1 percent moisture content.

Pine needles for the response time tests were preconditioned at a high humidity, 90 percent relative humidity at 75° F (24° C). When the needles were stabilized in moisture content at approximately 23 percent moisture content ovendry weight, a precalculated quantity of needles was weighed and transferred to the programable environmental chamber. In the chamber, with conditions at 90 percent relative humidity and 80° F (27° C), the litter beds were made to the desired bulk density on special aluminum weighing trays with solid bottoms and sides to minimize airflow within the litter bed (fig. 1).

The chamber and litter beds were conditioned as shown in figure 2. Adsorption test time was 24 to 48 hours, after which the litter beds were removed, weighed, and moisture content determined to provide a check of the weighing system's recorded weight change. These needles were discarded and another quantity of conditioned needles used for the next test.

The environmental chamber controls and air conditioning equipment are capable of making the change for 90 to 20 percent relative humidity in 60 minutes and from 20 to 90 percent relative humidity in 5 minutes. Some error in response time measurements can be caused by the response time of the chamber. Because pine needles have long response times (Simard 1968b; Van Wagner 1969; Fosberg 1975), greater than 4 hours, errors should be small.

The influence of solar heating upon the moisture response was investigated by running a second series of sorption tests using the solar heating capability of the environmental chamber. Nine overhead solar lamps provided the radiant heat simulating solar heating and were controlled by a pyroheliometer sensor and an electropneumatic recorder controller. A 3-mil Cu-Cn thermocouple was attached to the surface of a needle to monitor surface temperature on a strip-chart recorder. Solar heating was started at the beginning of the desorption run and maintained until the start of the adsorption run, when it was turned off. An intensity of about 0.6 solar constant (1.2 cal/cm^2-min) was used. These tests provided information on how response time was influenced by the additional temperature stress of solar heating.

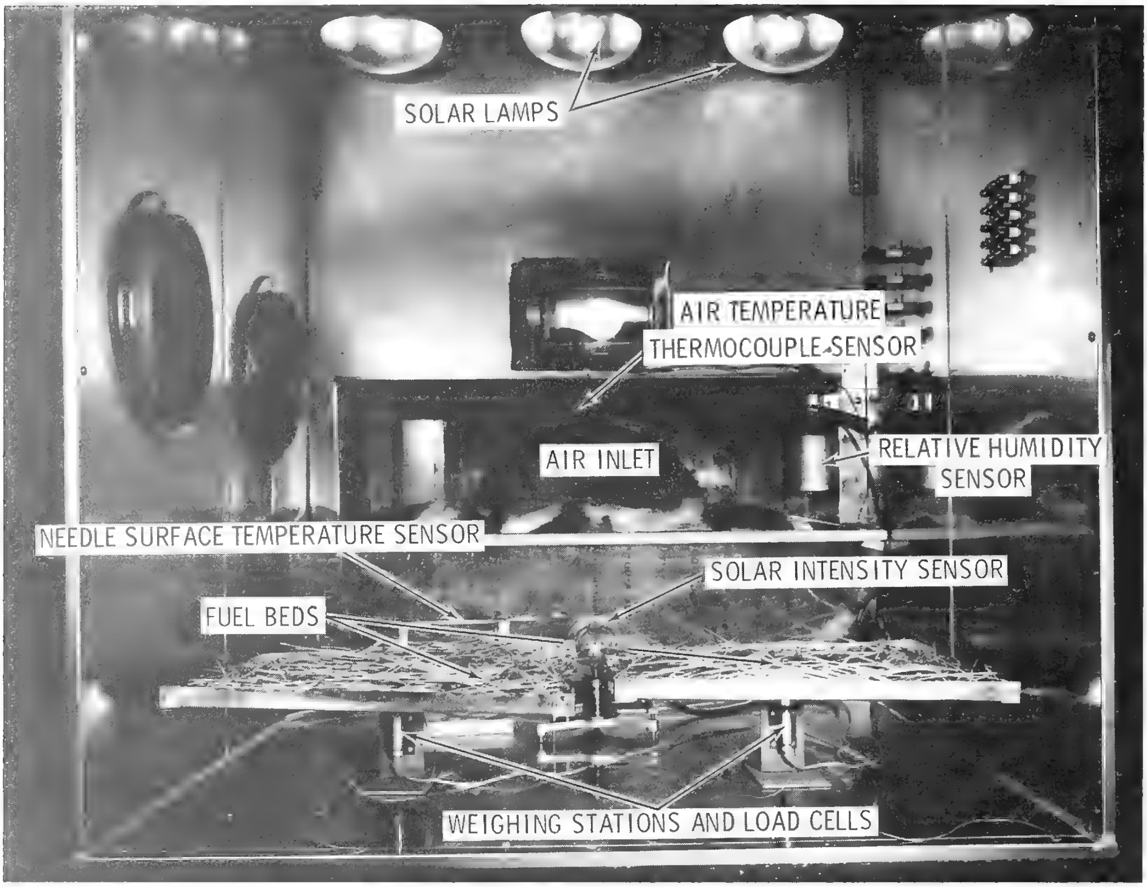

Figure 1.--Fuel bed located in environmental chamber.

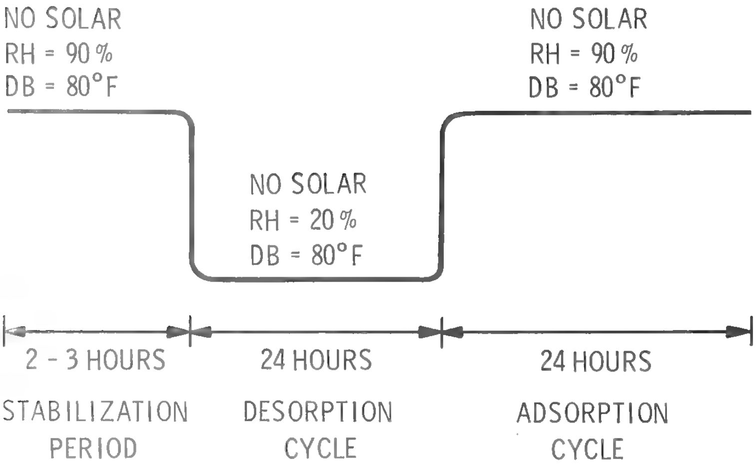

Figure 2.--The environmental conditions for the tests of moisture response time during first phase; a 0.6 solar constant was added for solar heating during the desorption cycle of the second phase of the tests.

RESULTS

Equilibrium Moisture Content

The sorption EMC tests were always started from a moisture content either higher or lower than any EMC expected. The desorption tests started from a high moisture content that ranged from 28.2 to 31.7 percent and averaged 29.6 percent. The adsorption tests started from a low moisture content between 2.6 and 3.4 percent that averaged 3.0 percent. The relative humidities used for conditioning and the EMC's that resulted are given in table 1. The differences between adsorption and desorption EMC's are less than 2.0 percent at humidities under 70 percent. Above 70 percent relative humidity, the difference became greater than 2.0 percent, approaching 3.5 percent at 90 percent relative humidity.

Table 1.--*Adsorption and desorption equilibrium moisture contents of ponderosa pine needles with starting moisture contents of 3.0 percent for adsorption and 29.6 percent for desorption*

Salt solution	Dry[1] bulb	Relative[2] humidity	Average adsorption moisture content	Average desorption moisture content	Hysteresis of moisture content
	°F	*Percent*			
LiCl	75	13	4.3 ±0.2	5.9 ±0.2	1.6
$MgCl_2$	75	33	7.5 ±0.4	9.0 ±0.0	1.5
$Mg(NO_3)_2$	75	53	10.2 ±0.2	11.9 ±0.1	1.8
NaCl	75	71	13.2 ±0.0	15.3 ±0.2	2.1
KNO_3	75	91	19.2 ±0.1	22.6 ±0.0	3.4

[1] Dry bulb temperature was maintained at 75°F ±5° (24° C ±2°).
[2] Relative humidity is the measured value and differs in some cases from values for chemically pure salts.

Moisture Response Time

Desorption and adsorption moisture response tests at 80° F (27° C) air temperature were run on individual needles and litter beds of the three bulk densities (fig. 3). The response time of materials to water vapor gradients is also called moisture timelag (Nelson 1969; Mutch and Gastineau 1970; Fosberg and Deeming 1971), and the moisture time constant (Van Wagner 1969). In each case, the expression is used to describe the exponential sorption process of the following equation (from Nelson 1969):

$$\frac{\bar{m} - m_e}{m_o - m_e} = E = K\exp(-t/\tau) \quad (1)$$

(Con.)

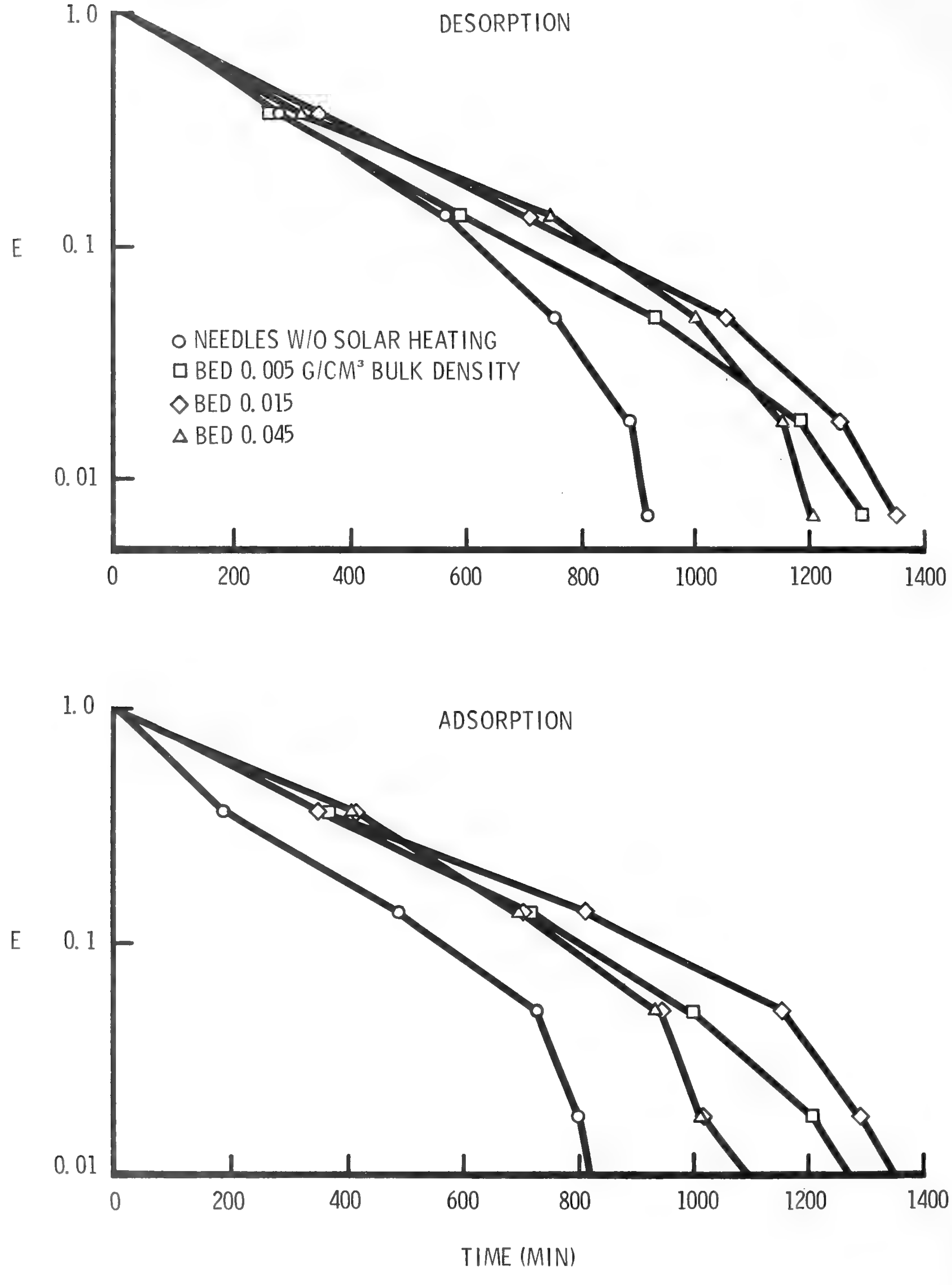

Figure 3.--Timelag response of ponderosa pine needles without solar heat (desorption).

where

$\bar{m}$ = average moisture content of needles or litter at time, t
m_e = equilibrium moisture content
m_o = initial moisture content
E = fraction of total evaporable moisture remaining in the fuel at time, t
K = dimensionless shape factor, assumed equal to 1.0
t = time, minutes
τ = response time, time constant, or timelag, minutes.

The descriptor, τ, represents the time required to proceed 63.2 percent, or (1 - 1/e), of the way to the total expected change. The time to achieve the total change can be broken in time periods. Each time period is the time to proceed 63.2 percent of the remaining portion of the total change and is tabulated in appendix table 5 for needles and table 6 for the adsorption and desorption tests without solar heating. The general trend shows an initial increase in time followed by a decrease as displayed in figure 4. This type of response has been reported by Nelson (1969), Mutch and Gastineau (1970), and Fosberg and others (1970).

The desorption tests with solar heating yielded shorter response times because solar heating at the 0.6 solar constant level increased needle surface temperature 23° F (-5° C). This caused a temperature gradient to be imposed on the vapor pressure gradient and shortened the response time, The adsorption runs following solar heating display a response not presently understood. The data for these runs are presented in table 7 of the appendix.

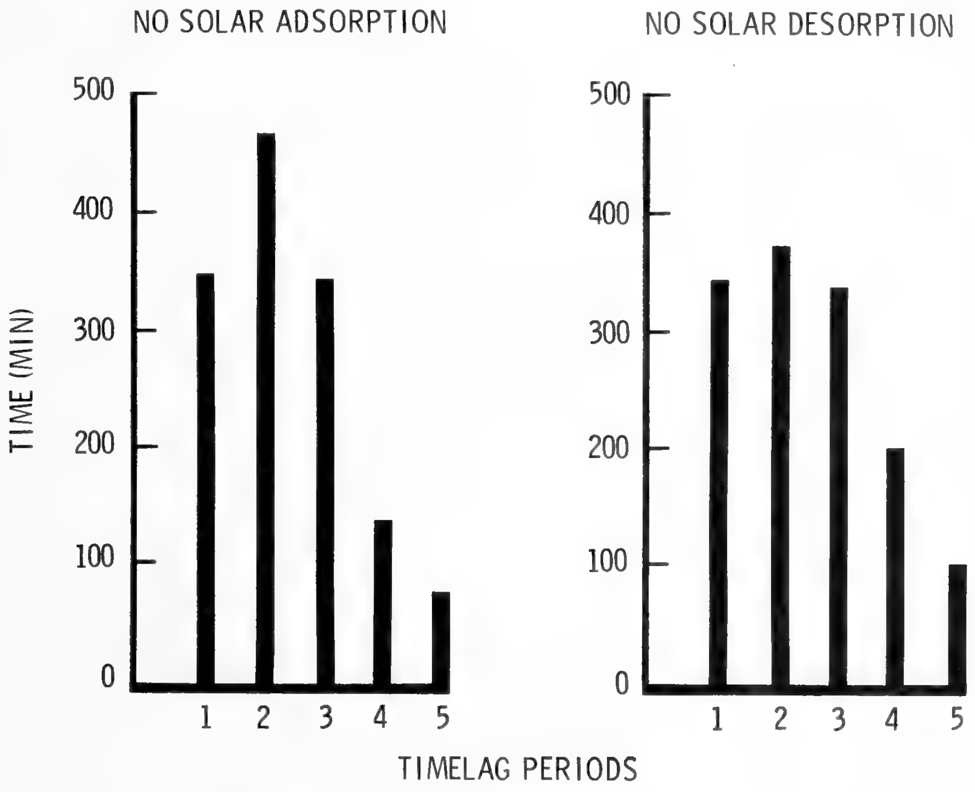

Figure 4.--Adsorption and desorption timelag periods for ponderosa pine needle beds at bulk density of 0.94 lb/ft^3 (0.015 g/cc).

DISCUSSION

Equilibrium Moisture Content

A variety of studies of individual fuel types have been conducted to determine the EMC's of wildland fuels (Dunlap;[2] King and Linton 1963; Blackmarr 1971; Van Wagner 1972; Britton and others 1973). However, Gisborne (1928) noted that tests by Dunlap[2] on woody samples of different species yielded results so nearly alike that a common EMC could be assigned to given relative humidities. Van Wagner (1972) found that leaf litter had higher EMC's than common woods by about 3 percent moisture content. Differences between leaf litter types were felt to have little practical importance for predicting fine fuel moisture content. However, Blackmarr (1971) and Van Wagner (1972) did observe an increase in EMC with weathering and aging which possibly is associated with the leaching of waxes and oils from the needles. The newly cast needles collected in September and October that we tested achieved EMC levels slightly lower than those found by Van Wagner for red pine needles.

The EMC data for ponderosa pine needles given in table 1 are plotted in figure 5 for adsorption and desorption. The curves displayed are from prediction equations generated from the data, according to the approach presented by Van Wagner (1972). The general form of the prediction equation is:

$$EMC = aH^{b} + c \cdot EXP\ [(H - 100)/d] + m(T_r - T) \tag{2}$$

where

EMC = equilibrium moisture content, percent ovendry weight
H = relative humidity, percent
T_r = reference temperature
T = temperature
a, b, c, d, m = coefficients dependent upon species, as noted by Van Wagner.

The last term adjusts for temperature which we did not test, but comparisons will be made to results obtained for ponderosa pine needles in other studies (Anderson 1964; Rothermel and Anderson 1966; Anderson 1969). These studies provide data on the adsorption equilibrium moisture content at 90° F (32° C) as ponderosa pine needles were conditioned for burning tests.

The coefficients of the terms in the equation were determined by first calculating a least squares fit for a power function, aH^b, up to 60 percent relative humidity for the first term. The calculated values of EMC were subtracted from the observed EMC

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[2] Dunlap, M. E. Forest Products Laboratory, Madison, Wisconsin; work cited by Gisborne (1928), p. 29.

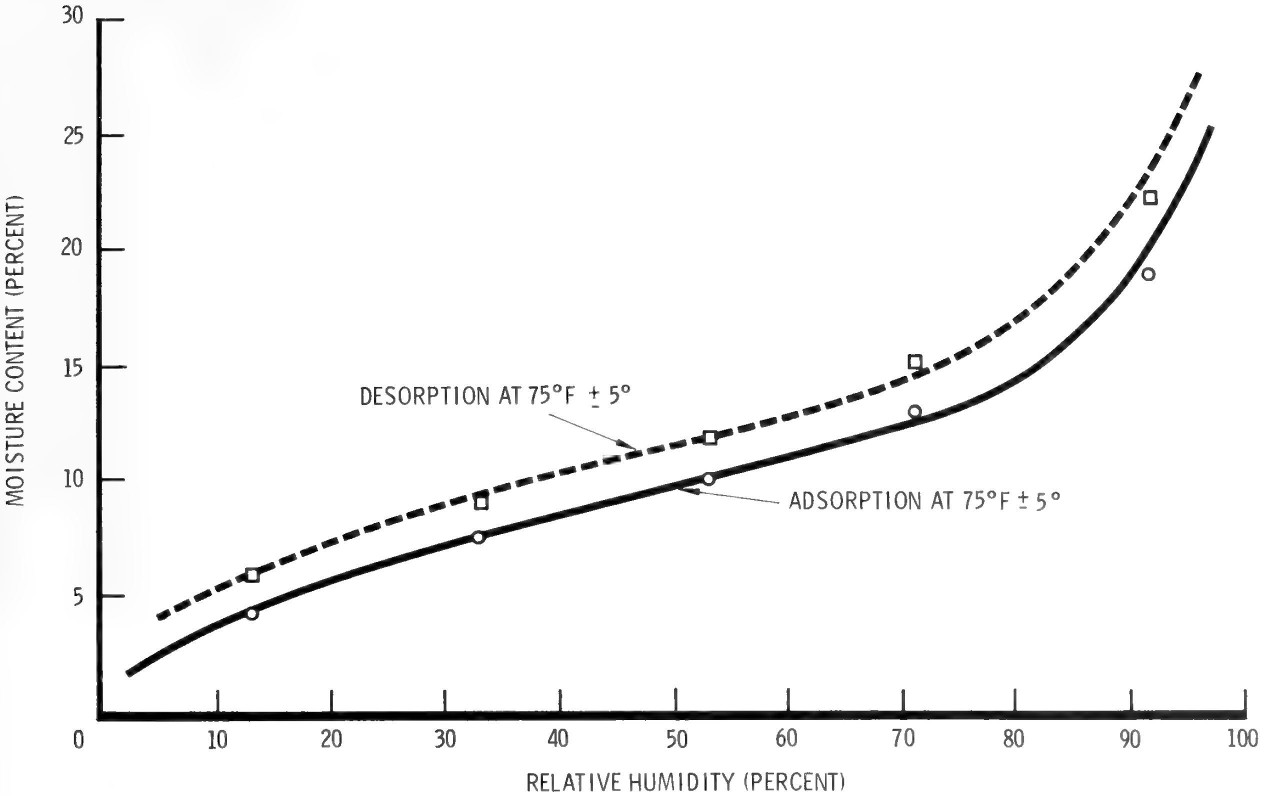

Figure 5.--Equilibrium moisture content data for adsorption and desorption with least squares fit curves from equations of the form, $EMC = aH^b + c \cdot EXP\ [(H - 100)/d]$ *for ponderosa pine needles.*

for each relative humidity and the difference used for a least squares fit to an exponential function, $c \cdot EXP\ [(H - 100)/d]$, from 50 percent relative humidity up to the maximum relative humidity. The overlap from 50 to 60 percent relative humidity provides a smooth transition and fit to the data. The coefficients, a, b, c, d, along with r_1 and r_2, correlation coefficients of moisture content to relative humidity for each portion of the equation, were determined to be:

	a	b	r_1	c	d	r_2
Adsorption	0.891	0.612	0.9998	17.54	8.91	0.9818
Desorption	1.651	.493	.9976	19.35	10.88	.9893

The curve in figure 5 shows the goodness of fit and shows the separation of the adsorption and desorption curves to be about 1.5 percent moisture content. Above 65 percent relative humidity, the separation continues to increase, reaching about 3.2 percent moisture content at 90 percent relative humidity.

Although the effect of temperature on EMC was not part of the tests reported here, the EMC curves were compared with earlier adsorption data (Anderson 1964; Rothermel and Anderson 1966; Anderson 1969). In the earlier tests, ponderosa pine needles were first ovendried. Then the needles were conditioned over saturated-salt solutions for different humidities at 90° F (32° C) until the needle moisture content had stabilized. These data were also fit to equation 2 and compared to the 75° F (24° C) data (fig. 6). A difference due to temperature appears from 20 to 80 percent relative humidity, but beyond these conditions the EMC values are essentially the same.

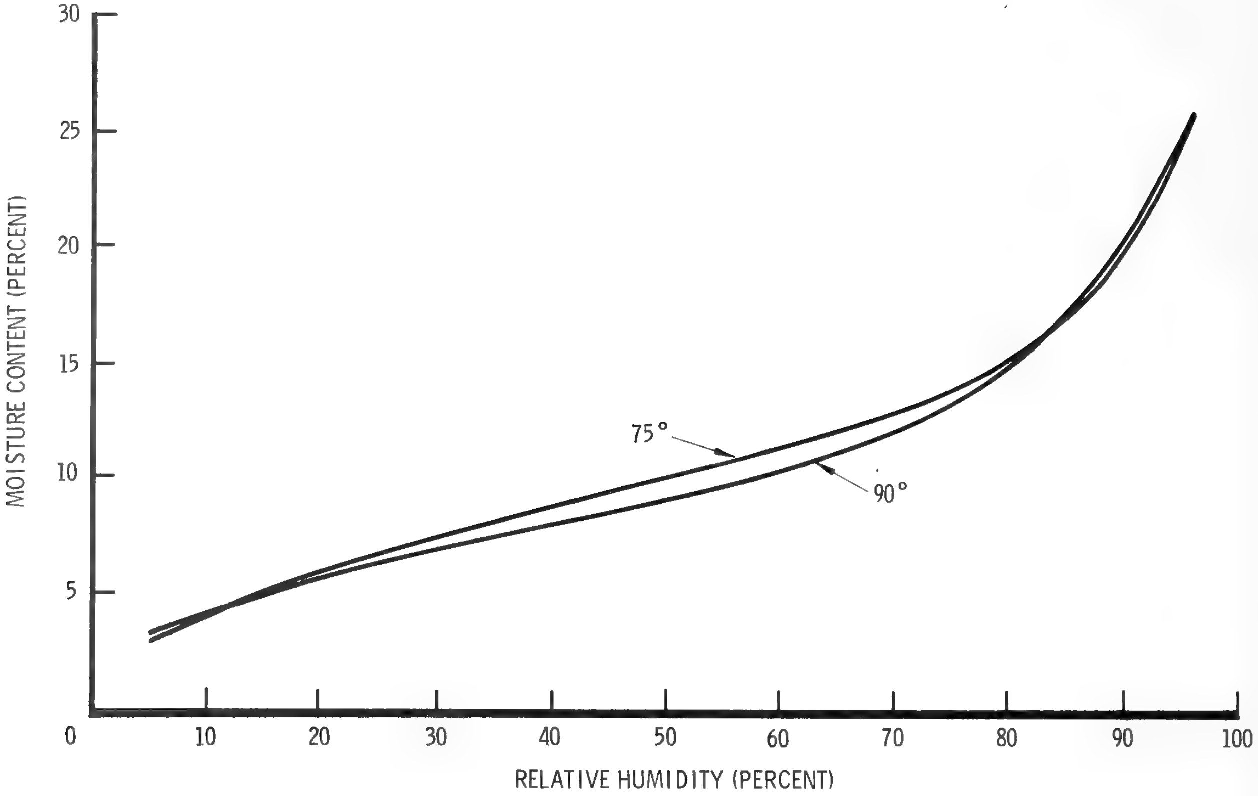

Figure 6.--Effect of temperature on adsorption EMC of ponderosa pine needles at 75° and 90° F.

Work by Spalt (1957) on basswood at 72° and 90° F (22° and 32° C) showed the same trend to convergence at each extreme (Byram).[1] The influence of temperature on EMC averaged 0.056 percent EMC per degree Fahrenheit. In addition, Gisborne (1928) reported on work by M. E. Dunlap for six fuel types that provided similar responses to temperature. A composite response for EMC change over the temperature range of 50° to 100° F (10° to 38° C) provided a temperature factor of 0.050 percent EMC per degree Fahrenheit. This is about half of what Van Wagner (1972) found for conifer litter, 0.113 percent EMC per degree Fahrenheit. The variation observed by Van Wagner suggests that additional study is needed to identify the magnitude of the temperature influence. In addition, he noted a difference between species in the EMC's established for given temperatures and humidities. For the ponderosa pine litter we tested, the EMC values for adsorption or desorption can be estimated by:

$$\text{Adsorption EMC} = 0.891\ H^{0.612} + 17.54\ \text{EXP}[(H - 100)/8.91] + 0.056(75 - T) \qquad (2A)$$

$$\text{Desorption EMC} = 1.651\ H^{0.493} + 19.35\ \text{EXP}[(H - 100)/10.88] + 0.056(75 - T) \qquad (2B)$$

where

H = relative humidity, percent
T = fuel surface temperature, °F.

Our EMC values were compared with EMC values for other fine forest fuels (King and Linton 1963; Stamm 1964; Rothermel and Anderson 1966; Anderson 1969; Blackmarr 1971; Van Wagner 1972). Monterey pine displayed EMC's about 2 percent lower than ponderosa

pine which was 1 to 2 percent lower than other conifer needles. Grasses and both evergreen and deciduous hardwood leaf litter maintain higher EMC's than ponderosa pine needles. The difference in EMC values becomes greater as the relative humidity increases above 60 percent and the EMC divergence can be as high as 9 percent moisture content. Van Wagner (1972) concluded that all kinds of leaf litter have EMC's about 3 percent higher than the common woods; this difference in EMC is felt to be definitely important in fire-danger rating.

The sorption data for various pine needles are within 2.5 percent moisture content of each other in 53 percent relative humidity and 75° to 80° F (24° to 27° C). However, when other fine fuels like grasses, hardwood leaves, and wood splints are considered (Stamm 1964; Blackmarr 1971; Van Wagner 1972), the variation becomes sufficient to reduce the accuracy of fire-danger estimates. Examination of the data at 53 percent relative humidity showed the adsorption EMC values ranged from 8.3 to 12.3 percent and the desorption values ranged from 10.9 to 15.5 percent for a total range of 7.2 percent moisture content in EMC. This suggests a composite estimate of fine fuel moisture may be no closer than ±3.6 percent moisture content to the real value.

Comparing the fine fuel moisture content isotherm of the Canadian Forest Fire Weather Index with the 1-hour timelag fuel moisture of the United States' National Fire-Danger Rating System (NFDRS) shows a similar difference, approximately 4 percent, in predicted moisture content. This appears to be due to the type of fuels considered in establishing the moisture content response. The Canadian system is based on the litter fuels in their coniferous forest (Van Wagner 1974; Van Wagner and Pickett 1975) and the United States' system is based on studies of fine woody materials (Fosberg and Deeming 1971). The ponderosa pine needle data (fig. 7) agrees with the Canadian isotherm at low humidities, but holds to lower moisture contents at humidities above 30 percent and agrees with the National Fire-Danger Rating System 1-hour fuel moisture content.

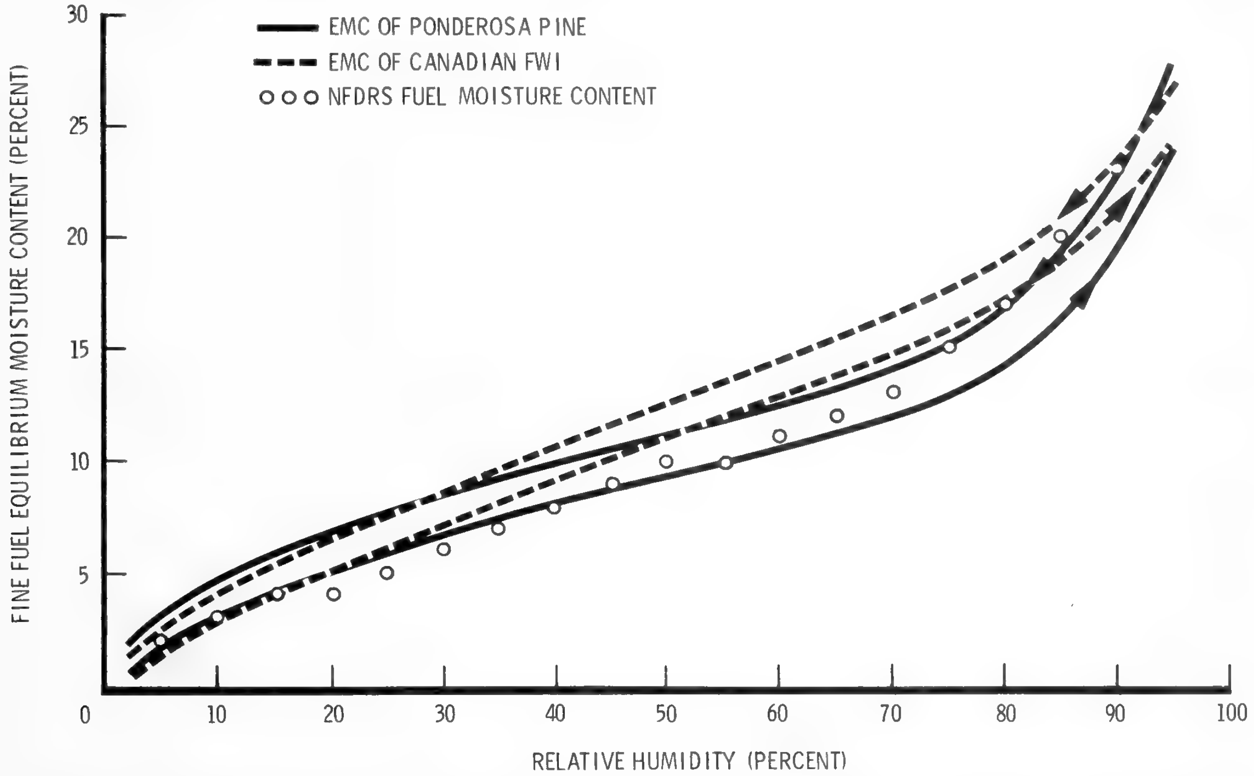

Figure 7.--Comparison of EMC values for ponderosa pine needles with fine fuel moisture content curve of Canadian Fire Weather Index and the USDA Forest Service NFDRS 1-hour timelag fuel moisture content data. Weather conditions -- 80° F and cloudy.

Allowance for specific fine fuel types may be necessary, particularly in areas where an index, such as the Ignition Index, is used administratively and is sensitive to fine fuel moisture content. For example, in an area where conditions can reach 80° F (27° C) and 20 percent relative humidity on a cloudy day, the NFDRS estimates nonliving fine fuel moisture content to be 4 percent. This may be 3 to 4 percent below the actual moisture content. This difference changes the Ignition Component from 65 to 38, which may be significant in a control unit's action plan. This type of sensitivity to fine fuel moisture content suggests that the measurement techniques and predictions of fine fuel moisture content be as accurate as possible.

Timelag

Ponderosa pine needles and litter beds exhibit similar timelag variability, but the similarity is less evident in litter bed test results (fig. 3). The variation in the timelag period may be due to the various factors influencing the diffusivity of the material. Byram[1] discussed control of moisture flow and thought that a forcing function of moisture content and saturation vapor pressure could effectively describe the change. This concept was expanded upon by Nelson (1969) and Fosberg (1970). Nelson showed that the diffusion theory could describe certain changes in moisture response of fine fuels, but such things as initial moisture content and relative humidity effects are not accurately predicted. Fosberg (1975) has developed a generalized approach to the theoretical solution using a timelag definition dependent upon physical properties of the material. He used boundary conditions that were difference approximations to the continuous change in temperature and relative humidity and noted that a different response time should be expected for each different set of initial conditions. The timelag has been associated with standard drying conditions of 80° F (27° C) and 20 percent relative humidity as noted by Nelson (1969) for NFDRS use. For constant conditions, timelag is expressed as a function of material thickness, moisture diffusivity, and a dimensionless number, defined as a Fourier number for moisture by Byram[1]. For our tests, we are starting from the standard set of conditions to establish a stable method of evaluating timelag and to indicate the effect of bed bulk density on timelag.

Previous work and our test results show the timelag response is curvilinear, yielding shorter times for the fourth and fifth time periods. The latter periods involve small changes in moisture content, so small errors in moisture measurement result in large variations in the time measurement. For these reasons, and because the first three periods account for 95 percent of the total change and exhibit a near linear response on semilog graph paper (fig. 3; that is, a constant log drying rate) we determined the average timelag from the time to achieve a 95 percent change in moisture content. The time to achieve a 95 percent change represents three time periods, so one-third of that total time is the average timelag for a run. The mean timelag for each litter bed and sorption condition are given in table 2, along with the physical properties of each litter bed test condition.

Comparison of the results obtained using five time periods, three time periods, or the time for a 95 percent change of each run to compute an average and standard deviation showed that less variability occurred with the time to 95 percent change. For the litter beds with a bulk density of 0.015 g/cc, the standard deviation decreased from 125 min for five time periods to 69 min for three time periods to 48 min for a 95 percent change. Although greater stability is indicated for the latter method, the standard deviation indicates considerable variability in the vegetative material and litter beds; this indicates a number of runs are needed to obtain a reliable mean.

Table 2.--*Mean timelags for needles and litter beds of ponderosa pine needles based on the time for 95 percent of total change*

Material	Physical properties: Thickness	Density	Packing ratio	Initial moisture content	Final moisture content	Response time data: Arithmetic mean	Standard deviation	No. of runs	Standard error
	Cm	*G/cc*		- - - *Percent* - -		- - - *Min* - - -			*Min*
				DESORPTION WITHOUT SOLAR					
Needles	0.0695	0.51	1.0	23.0	7.2	251.4	48.6	5	21.8
Bed	2.0	.005	0.0098	23.0	7.2	309.8	16.7	3	9.7
Bed	2.0	.015	.0294	23.0	7.2	350.4	48.2	6	19.7
Bed	2.0	.045	.0882	23.0	7.2	332.8	56.8	3	32.8
				ADSORPTION WITHOUT SOLAR					
Needles	.0695	.51	1.0	7.2	23.0	242.6	79.9	5	35.7
Bed	2.0	.005	.0098	7.2	23.0	333.1	91.8	2	64.9
Bed	2.0	.015	.0294	7.2	23.0	385.4	40.2	6	16.4
Bed	2.0	.045	.0882	7.2	23.0	314.5	14.4	3	8.3
				DESORPTION WITH SOLAR					
Bed	2.0	.005	.0098	23.0	7.2	243.3	70.4	4	35.2
Bed	2.0	.015	.0294	23.0	7.2	206.2	54.6	5	24.4
Bed	2.0	.045	.0882	23.0	7.2	154.0	24.5	4	12.3
				ADSORPTION AFTER SOLAR					
Bed	2.0	.005	.0098	7.2	23.0	382.9	54.6	4	27.3
Bed	2.0	.015	.0294	7.2	23.0	406.8	27.3	5	12.2
Bed	2.0	.045	.0882	7.2	23.0	411.3	18.1	4	9.1

The results for needles suggest nearly equal response times for desorption and adsorption. This timelag of 4.2 hours agrees with the needle timelag reported by Fosberg (1975) of 4.1 hours for freshly fallen ponderosa pine needles, as supplied by Blackmarr (1971). Data for other conifer needles, freshly cast, show variation in timelags:

Species	*Timelag*	*Drying condition*		*Reference*
	Hours	*°F*	*Percent relative humidity*	
Lodgepole pine	17.5	80	20	Blackmarr, in Fosberg (1975) (supported by our own tests)
Red pine	10.5	78 ±2	35 ±5	Van Wagner (1969)
Red pine	21.5	78 ±2	55 ±5	Simard (1968b)
Eastern white pine	17.5	78 ±2	55 ±5	Simard (1968b)
Jack pine	16.5	78 ±2	55 ±5	Simard (1968b)
White spruce	15.0	78 ±2	55 ±5	Simard (1968b)

The longer timelags may be partially due to the soaking before the test and the higher relative humidities used for end points. Only Blackmarr had end conditions similar to ours and although he presoaked the material, he obtained timelags comparable to ours.

Although we are not reporting results for weathered needles because tests are still being conducted, data in the literature show a dramatic shortening of the timelag:

Species	*Timelag*	*Drying condition*		*Reference*
	Hours	*°F*	*Percent relative humidity*	
Ponderosa pine	1.28	80	20	Fosberg (1975)
Lodgepole pine	1.01	80	20	Fosberg (1975)
Monterey pine	1.08	83	56	King and Linton (1963)
Red pine	4.20	78 ±2	35 ±5	Van Wagner (1969)
Red pine	7.00	78 ±2	55 ±5	Simard (1968b)
Eastern white pine	3.50	78 ±2	55 ±5	Simard (1968b)
Jack pine	4.00	78 ±2	55 ±5	Simard (1968b)
White spruce	5.00	78 ±2	55 ±5	Simard (1968b)

Variations in timelag may be due to the wax and resin content, as suggested by Van Wagner (1969). This could account for the shorter and variable timelags in weathered needles noted by Simard (1968b). It appears that the timelags are significantly different by species and weathering, which may be associated with the amount of waxes, oils, and varnishes on the surface and in the pores of the needles. Therefore, the results we are reporting probably only apply to freshly cast litter in ponderosa pine forests.

Generally, reports on timelags of fuels experiencing desorption or adsorption show the timelags to be longer for adsorption (Kerr and others 1971; Simard 1968b). Although the needle tests did not show this response, it did exist in the litter bed tests.

As the bulk density increased, the timelag increased but showed a leveling of timelag at the most dense value tested (fig. 8a). This leveling, or plateau, may be due to air velocities over and through the litter bed or may represent a zone of bulk densities where diffusion through the voids is limited by the moisture diffusivity of the particles. This consideration is pointed out by Fosberg (1975) in his theoretical development of heat and moisture flux in litter and duff. The responses obtained in this study tend to support the theoretical approach Fosberg has developed, but additional tests with varying bulk densities and litter depths are needed.

The desorption response of the litter bed with solar heating included appears to be inverse to the expected. Response time was found to become shorter as bulk density increased (fig. 8b) for desorption. With adsorption conditions established and solar heating turned off, the response is similar to previous adsorption tests. Some lengthening of timelag was observed, reflecting the thermal relaxation of stress back to ambient air temperature.

Little moisture response data are available to compare with theoretical developments such as Fosberg's (1975), but the litter bed tests we conducted at a bulk density of 2.81 lb/ft^3 (0.045 g/cc) were compared to the profiles Fosberg (1975) presented in figure 8 of his paper. Since the experimental measuring methods we used provided the average moisture content of the bed, comparison to Fosberg's theoretical results required averaging his moisture content profile at each depth over time. Both thermal

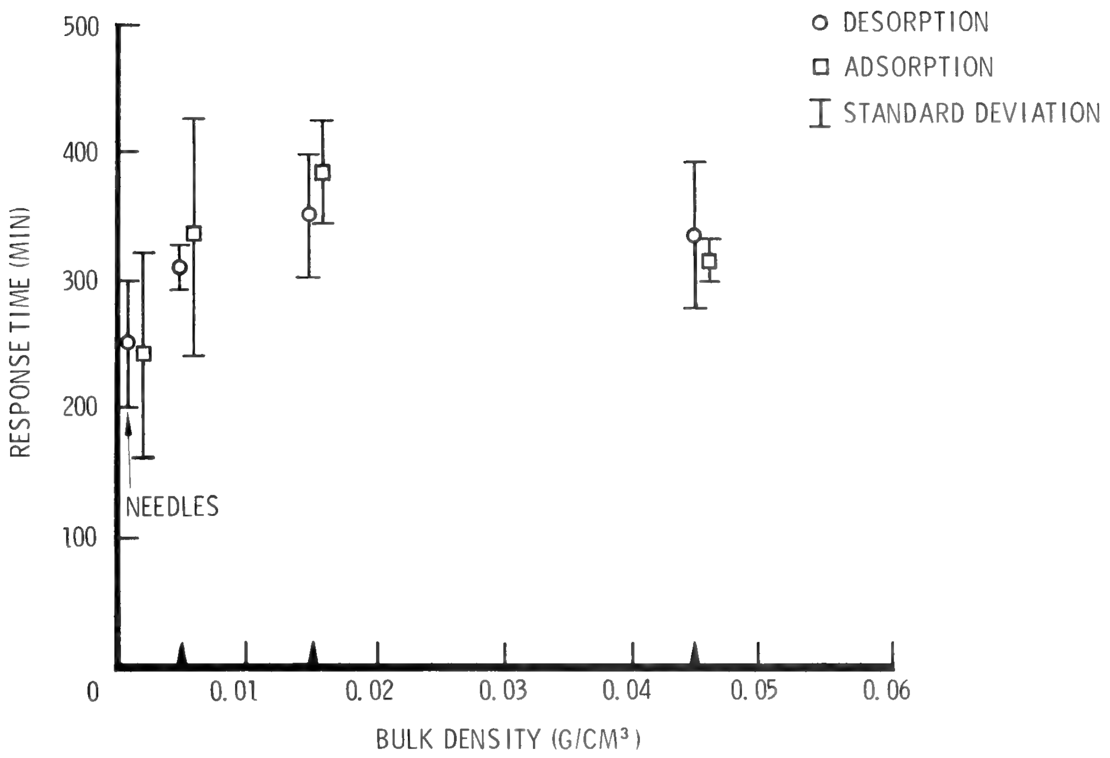

Figure 8A.--Response of timelag to changes in litter bed bulk density.

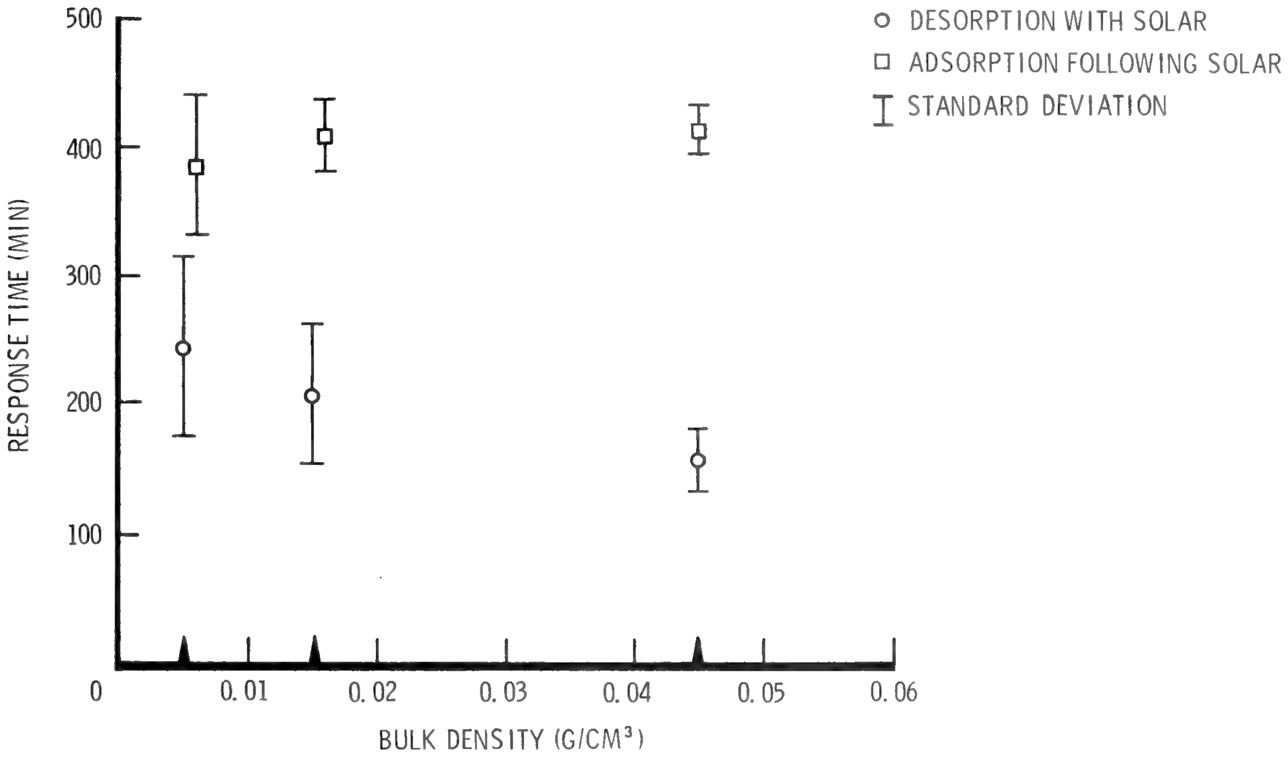

Figure 8B.--Response of timelag to changes in litter bed bulk density with or following solar heating.

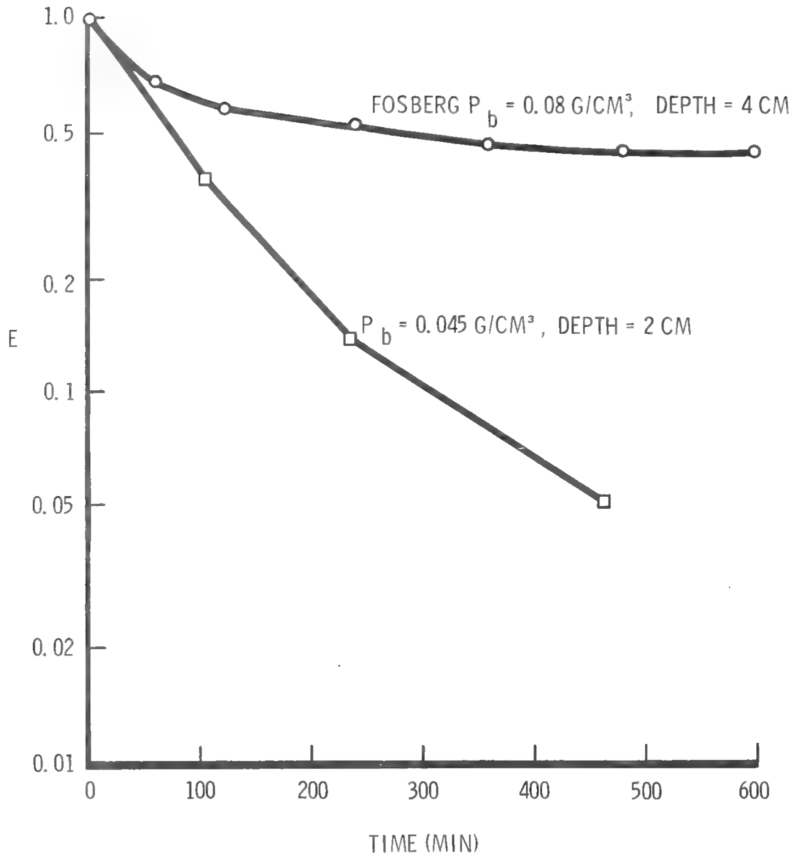

Figure 9.--Comparison of average moisture content for theoretical analysis of moisture content profile (Fosberg 1975) and experimental results for litter bed of ponderosa pine.

and moisture stress were imposed in both situations and the comparison shows that the theoretical approach does predict the timelag to increase with each successive time period (fig. 9). This behavior is found at each bulk density when solar heating was used and reflects the initial response to both the temperature and moisture changes followed by the response to moisture only, which has a longer timelag.

Moisture Diffusivity

It has been noted earlier that the timelag did not remain constant during the sorption process and the differences could be traced to the assumptions made in the theory of homogeneous physical properties and the diffusivity. Fosberg (1975) discussed the diffusivities involved and utilized them in the development of his theoretical approach. At least three degrees of diffusivity need to be considered; the diffusivity of the particles, of the voids, and the effective diffusivity of the litter layer.

For individual particles, it has been shown that the Fourier number for moisture describes the relationship of timelag, diffusivity, and particle thickness (Fosberg 1970; Fosberg and others 1970):

$$F_o = \nu/\lambda R^2 \qquad (3)$$

where

F_o = Fourier number, dimensionless
ν = diffusivity, cm^2/s
R = thickness, cm
$1/\lambda = \tau$ = timelag, s
λ = timelag reciprocal or decay coefficient, s^{-1}.

This equation relates to the equation for the integral diffusion coefficient, $\overline{D}$, described by Stamm and Nelson (1961) and Stamm (1964). In turn, Stamm states this resulted from Fick's general diffusion equation.

Stamm's equation for the integral diffusion coefficient can be rearranged to a form similar to equation (3):

$$\overline{D} = \nu = \frac{\pi E^2}{16} \frac{a^2}{t} \tag{4}$$

where

E = fraction of total change accomplished
$a = R$ = thickness, cm
t = time for change accomplished
π = 3.1416.

Rearrangement and common defining of terms lead to:

$$\frac{\pi E^2}{16} = \frac{\nu t}{R^2} \tag{5}$$

where the right-hand side is the same as the right-hand side of equation (3) except t is the time for the fraction of the total change, E, instead of $1/\lambda$ or τ, which is the timelag. Since the timelags for the data reported in this paper were calculated from the time for 95 percent of the total change, the diffusivity of the particles and the litter beds can be determined for the same conditions using equation (5):

$$\nu = \frac{\pi E^2}{16} \frac{R^2}{t} = \frac{\pi(0.95)^2}{16} \frac{R^2}{t} = 0.177 \frac{R^2}{t}. \tag{6}$$

The quantity, $\pi E^2/16$, of equations (4), (5), and (6) is a form of the Fourier number. With E equal to 95 percent of the total, the product is 0.177. This value agrees closely with values calculated from figure 2 of Fosberg's 1970 paper on drying rates of heartwood. If we could accurately determine when the total change has occurred, the value should approach 0.1963, $\pi/16$.

A summary of the timelags, thicknesses, and diffusivities is given in table 3. The range of diffusivities is shown in figure 10 which shows the diffusivities of the particles, the litter beds, and the voids. Both desorption and adsorption diffusivity changes with time are shown and indicate a common diffusivity is approached by both sorption processes. The diffusivities calculated using three timelag periods and 95 percent of the total change are slightly lower than diffusivities computed from specific fractions of total change and the time for the change. However, the differences do not appear significant.

The diffusivity of the voids was calculated from the diffusivity of free air at the test conditions and considering the porosity of the litter beds. The free air diffusivity was determined by the empirical equation used by Stamm and Nelson (1961):

$$\nu_o = 0.22 \left(\frac{T}{273}\right)^{1.75} \left(\frac{760}{P}\right) \mathrm{cm}^2/\mathrm{s} \tag{7}$$

where

T = temperature, °K
P = pressure, mm Hg = 760 EXP $[-(gh)/(RT_m)]$ (8)
g = 981 cm/s^2
h = elevation, cm
R = gas constant for air, $2.87 \times 10^6 \frac{\mathrm{cm - g}}{\mathrm{g - °K}}$
T_m = temperature at test, 300° K.

Table 3.--Moisture response properties of ponderosa pine needles and litter beds

Material	Density	Packing ratio	Thickness	Timelag	Diffusivity
	G/cm^3		Cm	S	Cm^2/s
		DESORPTION WITHOUT SOLAR			
Needles	0.51	1.0	0.0695	15,084	1.89×10^{-8}
Bed	.005	.0098	2.0	18,588	1.27×10^{-5}
Bed	.015	.0294	2.0	21,024	1.12×10^{-5}
Bed	.045	.0882	2.0	19,968	1.18×10^{-5}
		ADSORPTION WITHOUT SOLAR			
Needles	.51	1.0	.0695	14,556	1.96×10^{-8}
Bed	.005	.0098	2.0	19,986	1.18×10^{-5}
Bed	.015	.0294	2.0	23,124	1.02×10^{-5}
Bed	.045	.0882	2.0	18,870	1.25×10^{-5}
		DESORPTION WITH SOLAR			
Bed	.005	.0098	2.0	14,598	1.62×10^{-5}
Bed	.015	.0294	2.0	12,372	1.91×10^{-5}
Bed	.045	.0882	2.0	9,240	2.56×10^{-5}
		ADSORPTION AFTER SOLAR			
Bed	.005	.0098	2.0	22,974	1.03×10^{-5}
Bed	.015	.0294	2.0	24,408	9.68×10^{-6}
Bed	.045	.0882	2.0	24,678	9.57×10^{-6}

For the Missoula area, the diffusivity of the free air was calculated to be 0.292 cm^2/s. For the voids within the fuel beds, the approach cited by Fosberg (1975) was used. Work by Millington and Shearer (1971) shows the reduction in diffusivity to be a function of bed porosity:

$$\nu / \nu_o = \phi^{2x} \tag{9}$$

and the exponent, x, is defined by

$$\phi^{2x} \equiv 1 - (1 - \phi)^{x}, \text{ tortuosity factor} \tag{10}$$

where

ν_o = free air diffusivity, cm^2/s
ν = void diffusivity, cm^2/s
ϕ = bed porosity, fraction of volume, dimensionless.

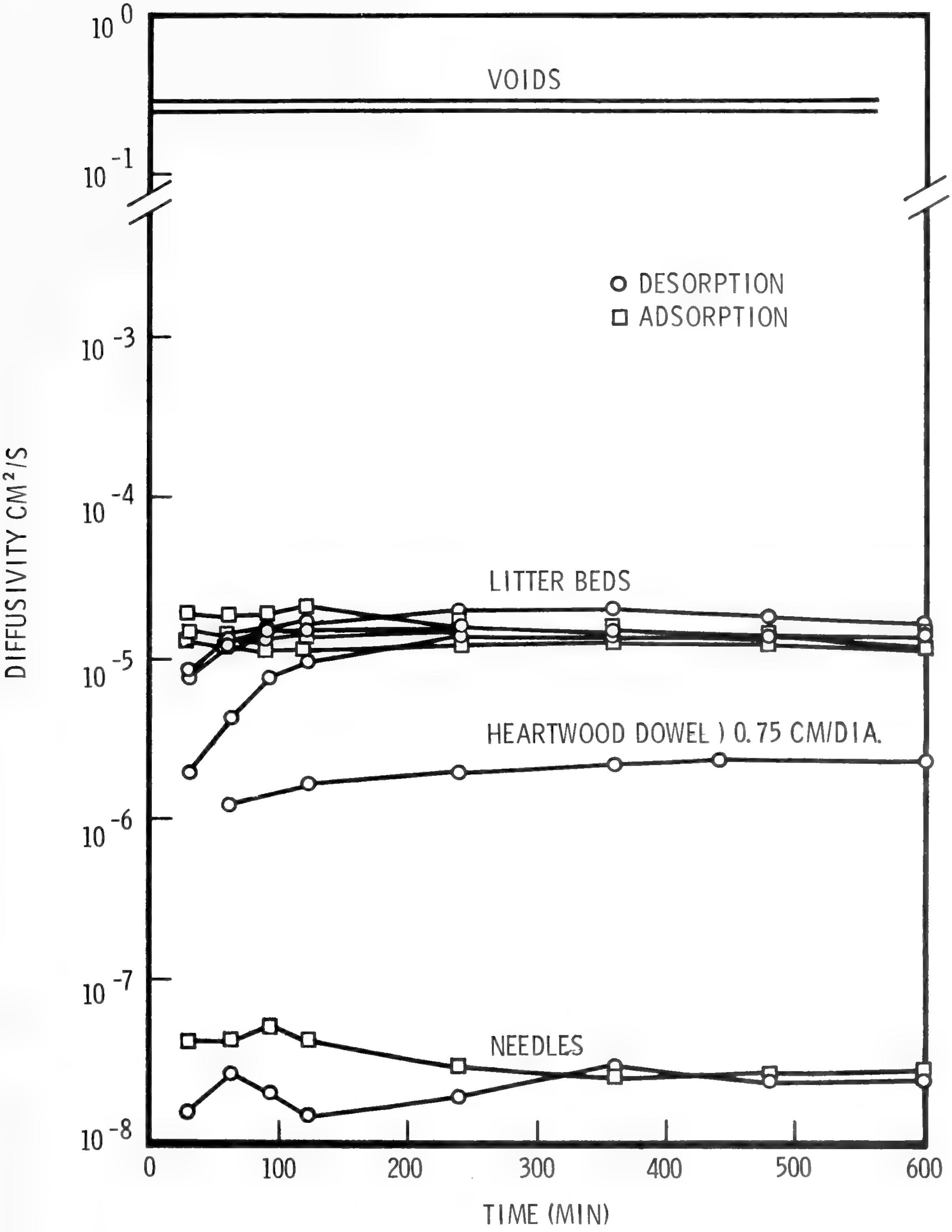

Figure 10.--Range of diffusivities determined for ponderosa pine needles, litter beds, and the voids within the bed.

Table 4.--*Comparison of diffusivity calculated for ponderosa pine litter beds under desorption conditions*

Physical properties	Fosberg (1975) 1	2	Anderson, Schuette, and Mutch 1	2	3
Fuel depth, H, (cm)	3	4	2	2	2
Bulk density, P_b, (g/cc)	0.08	0.08	0.005	0.015	0.045
Needle timelag, t, (s)	4,608	4,608	15,084	15,084	15,084
Free air diffusivity, ν_o, (cm^2/s)	0.313	0.313	0.292	0.292	0.292
Porosity, ϕ, (dimensionless)	0.830	0.830	0.990	0.971	0.912
Tortuosity factor, ϕ^{2x}, (dimensionless)	0.748	0.748	0.983	0.950	0.861
Void diffusivity, ν, (cm^2/s)	0.234	0.234	0.287	0.278	0.251
Litter bed timelag, t, (s)	4,248	7,560	18,588	21,024	19,968
Litter bed diffusivity, $\overline{\nu}$, (cm^2/s)	1.25×10^{-4}	1.25×10^{-4}	1.27×10^{-5}	1.12×10^{-5}	1.18×10^{-5}

The free air diffusivity was reduced by the above factor and the results for the litter beds compared to the predicted response of weathered ponderosa pine litter beds presented by Fosberg (1975) in his figures 2 through 5, table 4. Although the void diffusivities are not greatly different, the bed diffusivities differed by a factor of 10 when computed by equation (6). This is primarily a result of the longer particle and bed timelags existing in our experiments.

According to figure 9 of Fosberg's paper (1975), our experimental conditions appear to be at the limits of the theoretical considerations because our bed depth or thickness of 2 cm is in the zone where response time or timelag decreases as bulk density increases. As Fosberg notes, the timelag should increase as the bulk density increases and bed porosity decreases. Our results do not show a strong relationship between timelag and bulk density for the fuel loadings and depth we used.

Discussion of empirical refinements to improve the description of moisture diffusivity by Bramhall (1973) has proposed the inclusion of diffusivity as a linear function of moisture content. However, for litter beds and needles of ponderosa pine, the diffusivity appears to remain constant except for early in the sorption change. The same response of diffusivity is obtained using equation (6), as indicated in figure 10, for ponderosa pine heartwood dowels (Fosberg and others 1970). The value of 2.3×10^{-6} cm^2/s is higher than the value cited in the above work but is comparable to values cited by Stamm (1964) for various woods. The variation in diffusivity does appear to be nearly constant by species of material as long as the physical properties do not change. Then equation 3, 6, or equation 30 presented by Fosberg (1975) could be used to estimate the response time for a given fuel situation. If diffusivity is nearly constant and the thickness of material is known, response time can be readily calculated. For a given weather change in temperature and humidity, the time response can be considered with the EMC equations to estimate the moisture content of the litter and as related to flammability.

CONCLUSIONS

The equilibrium moisture content response curve of freshly cast ponderosa pine needles is lowest of the conifer needle data examined, except for Monterey pine. Differences between adsorption and desorption are slight (<1.5 percent) to 60 percent relative humidity, and the spread increases with increasing relative humidity. The EMC response can be described mathematically if temperature and humidity are known. Woody materials, such as twigs and splints of wood, maintain lower EMC's, while grasses and other herbaceous materials have higher EMC's, as much as 3 to 4 percent.

Temperature effects on EMC seem to vary by species and range from 0.050 to 0.113 percent moisture content per degrees Fahrenheit. Other changes in the litter material, such as crude fats, density, or possibly shape caused by weathering and aging, result in shifts in EMC values. Sufficient data are not available to fully assess these influences. However, they seem to influence both EMC values and timelag response.

Ponderosa pine needles, freshly cast, were found to have shorter timelags than other freshly cast conifer needles; approximately 4 hours as compared to 10 to 17 hours. It was noted in the literature that a year's weathering changes the timelag to a much shorter value, on the order of 1 hour. Although the change is felt to be associated with the leaching of the crude fat and other extractives, it is not known how rapidly the change in timelag occurs or what has been removed from the needles.

EMC and timelag values for ponderosa pine needles are sufficiently different from other species as to significantly affect the flammability of an area. The influence upon systems to assess fire danger should be determined so the use of fire-danger rating components and indices is as accurate as possible.

Use of the experimental data for fraction of moisture change and the time for the change showed moisture diffusivity to remain nearly constant during the response to the test conditions. However, just as air diffusivity is changed by pressure and temperatures, so may the moisture diffusivity of the litter material be changed. For litter beds with bulk densities between 0.31 lb/ft^3 (0.05 g/cc) and 2.81 lb/ft^3 (0.045 g/cc) the diffusivity was found to be 1.2×10^{-5} cm^2/s and for newly cast needles, 2.0×10^{-8} cm^2/s.

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APPENDIX

Sorption Time Constants for Single Ponderosa Pine Needles and Litter Beds

Table 5.--*Sorption time constants (in minutes) for a single ponderosa pine needle. Desorption conditions: 80° F (27° C) and humidity change from 90 to 20 percent. Adsorption conditions: 80°F and humidity change from 20 to 90 percent*

REPLICATES	Time period 1	2	3	4	5	Average
Desorption						
1	260	272	68	374	29	201
2	225	119	264	63	24	139
3	430	238	222	74	29	199
4	320	358	222	74	29	201
5	150	450	173	76	32	176
Average	277	287	190	132	29	
Adsorption						
1	110	169	141	134	29	117
2	90	317	213	62	24	141
3	379	179	102	37	15	142
4	148	206	582	87	36	212
5	192	650	161	41	17	212
Average	184	304	240	72	24	

Table 6.--*Sorption time constants (in minutes) for ponderosa pine needle litter beds. Desorption conditions: 80° F (27° C) and humidity change from 90 to 20 percent. Adsorption conditions: 80° F and humidity change from 20 to 90 percent*

REPLICATES	Time period					Average
	1	2	3	4	5	
	LOADING: BULK DENSITY 0.005 g/cm^3					
Desorption						
1	271.6	390.0	265.1	100.8	108.7	227.2
2	250.4	281.5	348.7	350.8	124.8	271.2
3	280.5	303.2	397.0	299.6	93.8	274.8
Average	267.5	324.9	336.9	250.4	109.1	
Adsorption						
1	1/ --	--	--	--	--	--
2	443.7	355.9	394.4	149.8	60.9	280.9
3	285.7	343.9	175.1	255.5	152.2	242.5
Average	364.7	349.9	284.8	202.7	106.6	
	LOADING: BULK DENSITY 0.015 g/cm^3					
Desorption						
1	356.3	439.6	482.1	87.5	40.1	281.1
2	285.0	317.5	346.8	294.7	96.2	268.0
3	451.8	372.6	298.8	129.0	91.8	268.8
4	384.6	434.4	243.0	216.0	84.0	272.4
5	264.4	315.0	279.3	320.9	148.9	265.7
6	307.3	346.4	383.0	149.3	139.7	265.1
Average	341.6	370.9	338.8	199.6	100.1	
Adsorption						
1	452.9	404.2	369.8	65.4	27.0	263.9
2	291.7	458.0	184.7	335.9	107.5	275.5
3	343.2	472.8	444.0	132.0	30.0	284.4
4	292.2	403.8	462.0	78.0	120.0	271.2
5	307.5	459.3	353.8	118.2	103.6	268.5
6	393.9	595.8	247.4	89.6	71.7	279.7
Average	346.9	465.6	343.6	136.5	76.6	
	LOADING: BULK DENSITY 0.045 g/cm^3					
Desorption						
1	271.1	351.8	194.4	120.0	52.4	197.9
2	312.8	413.9	296.0	210.2	55.1	257.6
3	371.5	514.5	269.2	120.2	66.1	268.3
Average	318.5	426.7	253.2	150.1	57.9	
Adsorption						
1	474.8	239.6	277.5	24.1	333.2	269.8
2	353.6	324.5	230.7	45.1	37.4	198.3
3	374.2	358.9	196.3	133.3	48.9	222.3
Average	401.0	307.7	234.8		139.8	

1/ Malfunction in the environmental chamber during absorption phase prevented the accumulation of data for the first run.

Table 7.--*Sorption time constants (in minutes) for ponderosa pine needle litter beds. Desorption conditions with solar hear: 80° F (27° C), 90 to 20 percent relative humidity, 0.6 solar constant. Adsorption conditions following solar heat: 80° F, 20 to 90 percent relative humidity, 0.0 solar constant*

REPLICATES	Time period 1	2	3	4	5	Average
		LOADING: BULK DENSITY 0.005 g/cm^3				
Desorption						
1	200.0	329.9	496.4	305.9	68.2	280.1
2	142.3	187.6	205.9	371.0	131.7	207.7
3	184.2	262.9	270.3	431.5	130.3	255.8
4	150.0	230.1	260.5	337.1	124.8	220.5
Average	169.1	252.6	308.3	361.4	113.7	
Adsorption						
1	297.2	518.3	521.4	73.2	19.0	285.8
2	320.3	423.7	263.3	379.3	33.8	284.1
3	360.5	563.5	310.7	92.0	33.8	272.1
4	291.7	388.9	334.9	198.9	28.9	248.6
Average	317.4	473.6	357.6	185.8	28.9	
		LOADING: BULK DENSITY 0.015 g/cm^3				
Desorption						
1	104.5	168.6	170.9	243.5	298.6	197.2
2	161.3	185.4	425.6	229.4	327.5	265.8
3	147.6	157.4	480.4	504.4	95.1	277.0
4	121.2	212.4	126.6	172.8	279.0	182.4
5	161.4	200.4	270.0	154.2	120.0	181.2
Average	139.2	184.8	294.7	260.9	224.0	
Adsorption						
1	535.1	418.9	276.5	137.7	47.5	283.1
2	473.0	434.9	203.7	93.9	34.5	248.0
3	483.6	520.0	336.2	70.8	18.6	285.8
4	444.0	426.0	325.8	64.2	132.0	278.4
5	462.0	478.0	283.8	126.0	42.0	278.4
Average	479.5	455.6	285.2	98.5	54.9	
		LOADING: BULK DENSITY 0.045 g/cm^3				
Desorption						
1	99.4	116.7	222.2	216.7	551.3	241.2
2	82.1	111.1	252.5	499.7	199.1	228.9
3	127.0	175.6	264.9	588.5	181.9	267.6
4	103.9	121.1	171.6	222.5	560.8	236.0
Average	103.1	131.1	227.8	381.8	373.3	
Adsorption						
1	520.8	472.0	264.1	102.9	47.1	281.4
2	504.2	466.6	233.0	150.2	54.4	281.7
3	604.5	490.8	203.2	105.6	22.7	285.4
4	578.1	419.7	179.1	188.2	41.9	281.4
Average	551.9	462.3	219.9	136.7	41.5	

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Anderson, Hal E., Robert D. Schuette, and Robert W. Mutch.
1978. Timelag and equilibrium moisture content of ponderosa pine needles. USDA For. Serv. Res. Pap. INT-202, 28 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

- Billings, Montana
- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)
- Reno, Nevada (in cooperation with the University of Nevada)